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Identification of a Novel Human Immunodeficiency Virus Type 1 Integrase Interactor, Gemin2, That Facilitates Efficient Viral cDNA Synthesis In Vivo

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Retroviral integrase (IN) catalyzes the integration of viral cDNA into a host chromosome. Additional roles have been suggested for IN, including uncoating, reverse transcription, and nuclear import of the human immunodeficiency virus type 1 (HIV-1) genome. However, the underlying mechanism is largely unknown. Here, using a yeast two-hybrid system, we identified a survival motor neuron (SMN)-interacting protein 1 (Gemin2) that binds to HIV-1 IN. Reduction of Gemin2 with small interfering RNA duplexes (siGemin2) dramatically reduced HIV-1 infection in human primary monocyte-derived macrophages and also reduced viral cDNA synthesis. In contrast, siGemin2 did not affect HIV-1 expression from the integrated proviral DNA. Although Gemin2 was undetectable in cell-free viral particles, coimmunoprecipitation experiments using FLAG-tagged Gemin2 strongly suggested that Gemin2 interacts with the incoming viral genome through IN. Further experiments reducing SMN or other SMN-interacting proteins suggested that Gemin2 might act on HIV-1 either alone or with unknown proteins to facilitate efficient viral cDNA synthesis soon after infection. Thus, we provide the evidence for a novel host protein that binds to HIV-1 IN and facilitates viral cDNA synthesis and subsequent steps that precede integration in vivo.

When a cell is infected with a retrovirus, the viral genome is subjected to several processes that include uncoating, reverse transcription of the viral genomic RNA into a cDNA copy by use of reverse transcriptase (RT), transport of this cDNA into the nucleus, and integration of the cDNA into the host chromosome. These early events are mediated through the interactions of several viral proteins and host factors with the viral genome, often referred as the reverse transcription complex or preintegration complex (4, 8, 16). The integration of a viral cDNA copy into a host cell chromosome is accomplished by integrase (IN) (24).

Mutational analyses of human immunodeficiency virus type 1 (HIV-1) IN have suggested putative roles for IN at steps prior to integration, such as uncoating (25, 29, 32), reverse transcription (11, 29, 37, 39), and nuclear import of viral cDNA (5, 20, 37). However, the mechanisms for these pleiotropic effects of IN mutations are largely unknown. Several cellular proteins, including integrase interactor 1 (23, 41) and human lens epithelium-derived growth factor-transcription coactivator p75 (27, 28), have been reported to interact directly with HIV-1 IN for chromosomal targeting of HIV-1 IN. Meanwhile, there has been increasing evidence of physical interactions between IN and RT during reverse transcription of HIV-1 (12, 19, 42), murine leukemia virus (MLV) (13), and *Saccharomyces cerevisiae* retrovirus-like element Ty3 (33). The results of an endogenous RT assay using purified HIV-1 virus particles also suggested that a cellular cofactor(s) might be required to complete reverse transcription in vivo (29).

In this study, we identified a novel host protein that binds to HIV-1 integrase and plays a critical role in HIV-1 infection in vivo. Survival motor neuron (SMN)-interacting protein 1 (Gemin2) (26) is a member of the SMN complex that mediates the assembly of spliceosomal small nuclear ribonucleoproteins (snRNPs) (3, 15, 21, 26, 30). Our results suggest that Gemin2 interacts with IN in the incoming virus genome complex and is essential for HIV-1 infection and viral cDNA synthesis and subsequent steps that proceed to integration.

MATERIALS AND METHODS

Plasmids. DNA fragments of the full-length HIV-1 IN were amplified by PCR from the HIV-1 pNL4-3lucΔenv vector by use of the oligonucleotide sense primer GBT9IN-1R (5′-CCGGAATTCTTTTTAGATGGAATA-3′) and the oligonucleotide antisense primer GBT9INenBH (5′-ACGGATCCTTAATCCT CATCCTG-3′). In the pNL4-3lucΔenv vector, the *env* gene has been deleted and the *nef* gene has been replaced with the firefly luciferase (Luc) gene (29). The amplified PCR products were digested with the restriction enzymes EcoRI and BamHI and ligated into the pGBT9 vector (BD Biosciences, San Jose, CA) (pGBT-IN). The pGBT9 vector constructs with truncated forms of IN (pGBT-ΔN-IN, pGBT-ΔN/ΔC-IN, and pGBT-INΔC) were similarly prepared using the following primer pairs: for pGBT-ΔN-IN, the sense primer GBT9IN50R (5′-CCGGAA TTCCATGGACAAGTAGAC-3′) and the antisense primer GBT9INenBH (corresponding to IN amino acid positions 51 to 288); for pGBT-ΔN/ΔC-IN, the sense primer GBT9IN50R and the antisense primer GBT9IN210BH (5′-ACGG ATCCAGTTTGTATGTCTGT-3′) (corresponding to IN amino acid positions 51 to 210); and for pGBT-IN-ΔC, the sense primer GBT9IN-1R and the antisense primer GBT9IN210BH (corresponding to IN amino acid positions 1 to 210). The pGAD-GH vector containing a HeLa cDNA library pretransformed into yeast strain Y187 was purchased from BD Biosciences. For preparation of a lentiviral vector expressing FLAG-tagged Gemin2, an EcoRI-XbaI fragment

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from pTRE-FLAG-Gemin2 (34) (kindly provided by G. Dreyfuss, University of Pennsylvania) was ligated into the pCSII-CMV-MCS vector (31) (kindly provided by H. Miyoshi, RIKEN Tsukuba Institute) or the pEF6/V5-HisA expression vector (Invitrogen). For construction of an small interfering RNA (siRNA)-resistant Gemin2 expression vector, silent point mutations were introduced into the target sequences of siGemin2#372 by use of mutagenic oligonucleotides (5′-CCTCCCTTGCTTAGCATCGTAAGCAGAATGAATC-3′).

Yeast mating and cDNA isolation. The pGBT-IN plasmid was transformed into yeast strain AH109, and yeast mating was performed according to the manufacturer's instructions (BD Biosciences). Positive transformants were verified for beta-galactosidase activity as described in the instructions.

Cells. HeLa and 293T cells were maintained in Dulbecco's modified Eagle's medium (DMEM; MP Biomedicals Inc., Irvine, CA) supplemented with 10% (vol/vol) heat-inactivated fetal bovine serum (FBS) (Invitrogen, Carlsbad, CA), 2 μg/ml sodium hydrogen carbonate (Wako, Osaka, Japan), 0.88 μg/ml tissue culture powdered DMEM amino acid and vitamin medium (Nissui Pharmaceutical Co., Ltd., Tokyo, Japan), 100 units/ml penicillin G, and 100 μg/ml streptomycin sulfate. Human peripheral blood mononuclear cells were isolated from HIV-1-seronegative healthy individuals by use of Ficoll-Paque Plus (Amersham Pharmacia Biotech Inc., Tokyo, Japan) density centrifugation. Human monocyte-derived macrophages (MDMs) were subsequently isolated from the peripheral blood mononuclear cells and cultured with RPMI 1640 (GIBCO, Invitrogen) supplemented with 5% human AB serum (Nippon Bio-supply Center, Tokyo, Japan) as described previously (37).

Construction of siRNAs. An siRNA duplex (small interfering green fluorescent protein [siGFP]) targeting the sequence 5′-AAGGUGCUCUGAAGUGA GGCU-3′ in the open reading frame of human Gemin2 (siGemin2) and a control double-stranded RNA targeting the 5′-CGGCAAGCUGACCCUGAA GUUC-3′ sequence in siGFP were purchased from QIAGEN K. K. (Tokyo, Japan). The targeting sequences of Gemin2 for the chemically modified synthetic siRNA duplexes (Stealth RNAi) purchased from Invitrogen were as follows: for siGemin2#372, 5′-CCU UGC UUA GUA UUG UUA GCA GAA U-3′; for siGemin2#373, 5′-GGA UAG CAA AGA UGA UGA GAG GGU U-3′; for siGemin2#374, 5′-UGA CCA ACG UGA UUU AGC UGA UGA G-3′; for siGemin2#375,5′-CAA GAA GGU GCU CUG AAG UGA GGC U-3′; for siGemin2#mm375, 5′-CAA GGA CGU UCU AAG GUG GAG AGC U-3′; for small interfering SMN#271 (siSMN#271), 5′-UAC UGG CUA UUA UAU GGG UUU CAG A-3′; for siSMN#272, 5′-CCA AAA GAA GAA UAC UGC AGC UUC C-3′; for siGemin3#430, 5′-CCA GUG AUC CAA GUC UCA UAG GUU U-3′; for siGemin3#431, 5′-GCU GCC GCU UCU CAU UCA UAU UAU U-3′; for siGemin3#432, 5′-GCU GUU GGA UCU CCU GGC AGA AUU A-3′; for siGemin4#354, 5′-GAA CUG CCU GAU GAG UCC CGU GAA A-3′; for siGemin4#355, 5′-AGG GAU UCC AGU GGC UGC UCU UCU U-3′; for siGemin4#356, 5′-UCU CGG AGA GGA UGC UGU CUC UCU U-3′; for siGemin6#950, 5′-CCC UUA GAA UGG CAA GAU UAC AUU U-3′; for siGemin6#951, 5′-GCA AAG CAU ACA GCC CAG AGG AUC U-3′; and for siGemin6#952, 5′-UCU GUC GCG UGU UCA GGA UCU UAU U-3′.

Transfection of siRNA. Cells were transfected with 40 nM of siRNA (siGemin2 or siGFP) by use of Oligofectamine or Lipofectamine 2000 (Invitrogen, CA). After 4 h of incubation, the cells transfected with the siRNA were added to 250 μl DMEM supplemented with 30% (vol/vol) heat-inactivated FBS. After 12 to 18 h of incubation, the transfected cells were washed and replaced with DMEM supplemented with 10% (vol/vol) heat-inactivated FBS, 100 units/ml penicillin G, and 100 μg/ml streptomycin sulfate. After 24 h of incubation, the siRNA duplex was transfected again to achieve efficient depletion of the target protein.

Virus preparation and infection. Pseudotyped viruses were generated as described previously (29). Briefly, 293T cells were transfected with the pNL43lucΔenv vector together with an ampho-MLV (pJD-1) (29) or vesicular stomatitis virus-G expression vector (pHCMVG) (40) by use of Lipofectamine (Invitrogen). The culture supernatants of the transfected cells (5 ml) were harvested 48 h posttransfection, filtered through 0.45-mm-pore-size filters, and used as virus preparations. The virus preparation was treated with DNase I (Worthington, Lakewood, NJ) (20 μg/ml) in the presence of 10 mM $MgCl_2$ at 37°C for 40 min to avoid plasmid DNA contamination. An aliquot of the virus preparation was incubated at 65°C for 30 min and used as a heat-inactivated control. To monitor the amount of virus in each preparation, HIV-1 p24 antigen levels were determined using an enzyme-linked immunosorbent assay. To monitor viral gene expression from each plasmid vector, luciferase activity in the transfected cells was also measured. At 48 h posttransfection, the 293T cells were lysed with 1 ml of 1× cell culture lysis reagent (Promega, Madison, WI), and 10 μl of each cell lysate was subjected to the luciferase assay. After incubation for 6 h, the viruses were removed and the cells were washed and incubated with fresh culture medium at 37°C in a 5% CO_2 incubator.

Analysis of HIV-1 cDNA synthesis. Total cells were harvested from each well periodically after infection with pseudotyped viruses. After washes with phosphate-buffered saline (PBS), total DNA was extracted by the urea-lysis method (29). Quantitative analyses of the amplified products and the rate of viral cDNA synthesis were performed using real-time quantitative PCR (LightCycler; Roche Diagnostics, Mannheim, Germany) as described previously (20).

Antibodies. The anti-Gemin2 monoclonal antibody (MAb), the anti-Ran MAb, and the anti-SMN MAb were purchased from BD Bioscience. The anti-Gemin3 MAb was purchased from ImmuQuest (ImmuQuest Ltd., Barwick TS175AL, United Kingdom). The anti-Gemin4 and anti-Gemin6 MAbs were purchased from Santa Cruz Biotechnology Inc. (Santa Cruz, CA). Anti-HIV-1 IN MAb was purchased from Microbix Biosystems Inc. (Toronto, Canada). Anti-HIV-1 p24 MAb was purchased from Chemicon International (Temecula, CA).

GST pull-down assay. DNA fragments encoding the N-terminal (amino acid positions 1 to 55), central (amino acid positions 50 to 212), and C-terminal (amino acid positions 213 to 288) HIV-1 IN regions or full-length (amino acid positions 1 to 288) HIV-1 IN were amplified by PCR using pNL43lucΔenv as a template. The amplified products were ligated to BamHI-EcoRI-digested pGEX-2T vector (Amersham Pharmacia Biosciences Inc., Uppsala, Sweden). Recombinant glutathione-*S*-transferase (GST)–IN was prepared as described previously (20). HeLa cell lysate (100 to 200 μg) was incubated with each GST-IN protein (200 nM) immobilized on glutathione-Sepharose beads in binding buffer (1.0% Triton X-100-1 mM phenylmethylsulfonyl fluoride in 1× PBS) for 15 min at 4°C. The beads were then washed five times with wash buffer (0.3% Triton X-100 in 1× PBS) and eluted with elution buffer. An aliquot of the pulled-down fraction was subjected to sodium dodecyl sulfate–12% polyacrylamide gel electrophoresis and Western blotting analysis.

Immunoprecipitation experiments. Total cell extracts were prepared as described previously (34). Briefly, cell pellets were suspended in RSB-100 (10 mM Tris-HCl [pH 7.4], 2.5 mM $MgCl_2$, 100 mM $NaCl_2$) containing 0.1% Nonidet P-40 and protease inhibitors followed by centrifugation at 10,000 × g for 15 min. Extracts were incubated with an anti-FLAG antibody (Sigma) for 1 h and subjected to immunoprecipitation using the Catch and Release system according to the manufacturer's instructions (Upstate, Lake Placid, NY).

RESULTS

Identification of a cellular factor that binds to HIV-1 IN. To identify host proteins that bind to HIV-1 IN, we used the yeast two-hybrid system and the yeast-mating method (BD Biosciences, San Jose, CA). A plasmid carrying the entire HIV-1 IN fused with the GAL4 DNA binding domain-coding region (pGBT-IN) was used as a bait vector. Five positive-testing clones were obtained from $\sim 2 \times 10^7$ prey plasmids containing a human HeLa cDNA library expressed as GAL4 activation domain fusion proteins. DNA sequence analysis of three of these positive-testing clones resulted in identification of a single cDNA clone encoding an amino acid fragment corresponding to residues 137 to 238 of SMN-interacting protein 1 (Gemin2; formerly SIP1) (26). We therefore termed residues 137 to 238 of Gemin2 IBDG2 (for "IN binding region of Gemin2"). Various bait vectors carrying the full-length or truncated forms of HIV-1 IN were cotransformed with the GAL4 activation domain vector carrying IBDG2 (pGAD-IBDG2) into yeast strain AH109 or HF7c. HIV-1 IN comprises three distinct functional domains (10, 38). Deletion of the COOH-terminal domain of IN (pGBT-DC-IN) significantly reduced the binding of IN to IBDG2, whereas deletion of the NH_2-terminal domain of IN (pGBT-DN-IN) had little effect on the binding activity (Fig. 1A). Deletion of both the NH_2-terminal and the COOH-terminal domains (pGBT-DN/DC-IN) resulted in low-level but significant binding to IBDG2. These results suggest that the COOH-terminal domain of the IN is the minimum domain responsible

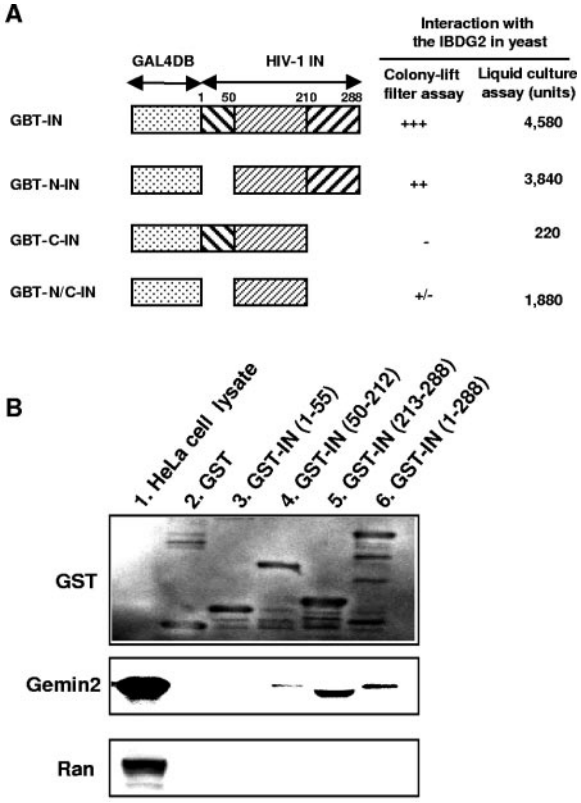

FIG. 1. Interaction of IN with Gemin2. (A) Yeast AH109 or HF7c cells were cotransformed with the pGAD-IBDG2 vector carrying the IBDG2 domain of Gemin2 together with various pGBT9 plasmids carrying full-length (pGBT-IN) or truncated (pGBT-DN-IN, pGBT-DC-IN, and pGBT-DN/DC-IN) forms of HIV-1 IN. Dashed boxes in the diagram indicate the region of HIV-1 IN retained in each pGBT-IN vector. The amino acid positions of HIV-1 IN are numbered according to the NL43 sequence. Interaction of coexpressed proteins was determined with a beta-galactosidase colony-lift filter assay (+++, dark-blue colony; +, medium-blue colony; +/−, light-blue colony; −, white colony) or a liquid-culture assay for estimating beta-galactosidase activity (expressed in units). The value for bait vector only (pGBT-IN) was used as the background value for the liquid-culture assay. (B) Untreated (lane 1) or pull-down (lanes 2 to 6) fractions of HeLa cell lysates on glutathione-Sepharose beads bound to GST-IN protein containing the N-terminal (1-55), central (50-212), C-terminal (213-288), or full-length (1-288) HIV-1 IN were subjected to Western blotting analysis using anti-GST, anti-Gemin2, and noninteracting (control) anti-Ran antibodies.

for the binding to the IBDG2 and that the central domain of IN partly contributed to the binding. We next examined the specific interaction of HIV-1 IN with endogenous Gemin2 in human cells. Recombinant GST fused with the entire IN protein or with the NH_2-terminal, central core, or COOH-terminal domain of HIV-1 IN was used for the pull-down experiment (Fig. 1B). Neither the NH_2-terminal domain of IN (GST-IN1-55) nor the control GST showed any specific binding activity to the endogenous Gemin2; however, the COOH-terminal domain of IN (GST-IN213-288) and full-length IN (GST-IN1-288) each bound to Gemin2. The central core domain of IN (GST-IN55-212) also bound to Gemin2 but with much weaker affinity than the COOH-terminal domain (GST-IN213-288). Thus, we confirmed that HIV-1 IN interacts specifically with full-length Gemin2 endogenously expressed in human cells.

Interaction of Gemin2 with IN of HIV-1 preintegration complex. Gemin2 interacts tightly with the SMN protein to form a macromolecular complex termed the SMN complex (26, 35). To address the interaction of Gemin2 and HIV-1 IN during the viral infection cycle, we first measured the amounts of Gemin2 and other constituents of the SMN complex (SMN and Gemin3) (6, 26) in purified, cell-free virus particles. None of these proteins were detected in the virus particles (Fig. 2A), suggesting that Gemin2 was not incorporated into HIV-1 virus particles. We next used coimmunoprecipitation to address the interaction of Gemin2 and IN during acute infection of HIV-1. Since the antibodies for Gemin2 or HIV-1 IN were available only for immunoblotting but not for immunoprecipitation, we used a lentivirus-vector gene delivery system to transduce FLAG-tagged Gemin2 (34) into HeLa cells (Fig. 2B). The HeLa cells expressing FLAG-tagged Gemin2 (Flag-Gemin2/HeLa) or control HeLa cells transduced with empty vector were infected with HIV-1 pseudotype virus. At 2 or 6 h postinfection, IN efficiently coimmunoprecipitated with FLAG-Gemin2 in the Flag-Gemin2/HeLa cell extract (Fig. 2C), and a significant amount of HIV-1 cDNA synthesized de novo was detected by PCR at each time point. The HIV-1 cDNA in the similarly prepared immunoprecipitate (IP) fraction from the control HeLa cells was below the detectable level following infection (Fig. 2D, upper panel). Quantitative PCR analysis of the HIV-1 cDNA in the IP fraction of the Flag-Gemin2/HeLa cells at 2 h and 6 h postinfection showed that 1,200 and 2,500 copies were present, respectively (Fig. 2D, lower panel), corresponding to 10% to 20% of the total cDNA in the input fraction at each time point. These results suggest that Gemin2 might interact with an incoming HIV-1 preintegration complex through IN after the entry and uncoating of viral genome.

Functional role of Gemin2 during the HIV-1 cycle. We next addressed the functional role of Gemin2 during the HIV-1 infection cycle by using the siRNA technique (36) to specifically deplete Gemin2 from cells. We directed the 21-nucleotide siRNA duplexes (9) against a coding region of the Gemin2 gene (siGemin2). The level of Gemin2 was monitored periodically after siRNA transfection. A reduction in the Gemin2 level was evident 1 day after the siRNA transfection and persisted for at least 4 days in culture (data not shown). At 48 h post-siRNA transfection, the siGemin2 specifically reduced the level of Gemin2 to from 20% to 40% of the level seen with the mock-treated or negative-control siGFP-treated HeLa cells (Fig. 3A). Slight reductions in levels of the SMN complex constituents, SMN and Gemin3 (6), were also noticed following the siGemin2 treatment.

Since the SMN complex regulates the biogenesis of the snRNP complex, we first examined the effects of siGemin2 on gene expression from the HIV-1 provirus and the infectivity of progeny viruses. siGemin2 or a control siGFP duplex (siCont) was cotransfected into 293T cells with an HIV-1 molecular clone, pNL43lucΔenv, and a vector expressing an amphotropic MLV or vesicular stomatitis virus-G envelope for a subsequent single-round infection assay. We measured the levels of p24 (HIV-1 capsid protein) 48 h after transfection. The amount of HIV-1 p24 in the culture supernatants of the siGemin2-transfected 293T cells was comparable to that in control and siCont-

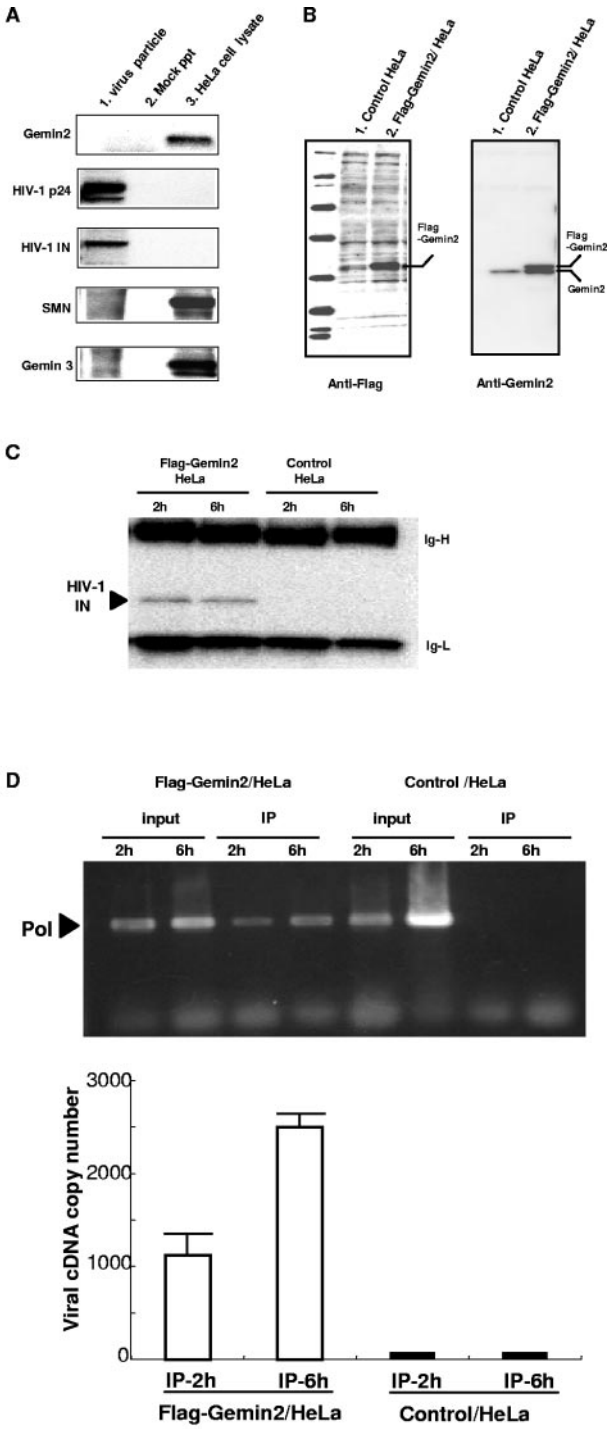

FIG. 2. Gemin2 interacts with the incoming HIV-1 genome complex. (A) Virus particles in the culture supernatant of 293T cells cotransfected with pNL43lucΔenv and pHCMVG were pelleted by ultracentrifugation (1 h at 315,000 × *g*) and subjected to Western blotting analysis using anti-Gemin2, anti-HIV-1 IN, or anti-p24 antibodies. Similarly prepared pellet fractions from mock-transfected cell supernatants (Mock ppt) and a HeLa whole-cell lysate were used as negative and positive controls, respectively. (B) HeLa cells were transduced with an empty vector (Control HeLa) or a FLAG-tagged Gemin2-expressing lentiviral vector (Flag-Gemin2/HeLa) and then subjected to Western blotting using an anti-FLAG antibody (left panel) or anti-Gemin2 antibody (right panel). (C) The transduced HeLa cells were infected with HIV-1 pseudotype virus. At 2 or 6 h postinfection, the cell lysates were immunoprecipitated with an anti-FLAG antibody and then subjected to Western blotting using an HIV-1 IN antibody. IgH, immunoglobulin heavy chain; IgL, immunoglobulin light chain. (D) Nucleic acids extracted from whole-cell lysates (input) or the IP obtained as described for panel C were subjected to PCR analysis of HIV-1 cDNAs. Amplified products (Pol) were separated in a 2% agarose gel and visualized by SYBR green staining (upper). The copy number of viral cDNA (R/gag) in each sample was estimated with real-time quantitative PCR (lower panel). Means ± standard errors (SE) from triplicate assays are shown.

transfected 293T cells (Fig. 3B, left panel). Furthermore, the progeny viruses released from the siGemin2-transfected 293T cell retained their infectivity (Fig. 3B, right panel). Thus, depletion of Gemin2 did not lead to any significant effect on proviral gene expression, virus release, or subsequent viral infectivity.

In contrast, HIV-1 infectivity was significantly reduced when the siGemin2 duplex was introduced into cells before viral infection (Fig. 3C). To exclude nonspecific or off-target effects (22) of the siGemin2 duplex originally tested here, we used four additional chemically modified synthetic siRNA duplexes (Stealth RNAi; Invitrogen) targeting different sequences within Gemin2 (Gemin2#372, Gemin2#373, Gemin2#374, and Gemin2#375) and an siGemin2 duplex carrying several nucleotide substitutions as a mismatch siGemin2 control (mm375). We observed significant reductions of HIV-1 infectivity that correlated well with the amount of specific reduction of Gemin2 with each type of siRNA treatment (Fig. 3C). In addition, we constructed an siRNA-resistant Gemin2 expression vector carrying silent point mutations in the target sequences of siGemin2#372. The siRNA-resistant Gemin2 continued to be expressed in the presence of siGemin2#372, but expression of the endogenous Gemin2 was greatly reduced (Fig. 3D lower). Under this condition, the siRNA-resistant Gemin2 rescued HIV-1 infectivity in siGemin2-treated cells (Fig. 3D upper). These results strongly suggest the functional role of Gemin2 through interaction with incoming HIV-1 genome complexes during the early steps of HIV-1 infection.

Functional role of Gemin2 in HIV-1 infection of primary nondividing cells. Next, we addressed the functional role of Gemin2 in HIV-1 infection of human primary MDMs, a model of major natural targets for HIV-1 infection in vivo. MDMs were isolated from three different healthy donors. Transfection of siGemin2 into MDMs markedly reduced HIV-1 infectivity to from 0.3% to 10% of the levels in the control MDMs (Fig. 4B, left panel). This remarkable effect of siGemin2 observed in MDMs could be partly explained by the fact that primary MDMs constitutively express a lower level of Gemin2 than the 293T and HeLa cell lines, which have been adapted in vitro (Fig. 4A). We confirmed that reduction of Gemin2 also suppressed spreading of replication-competent HIV-1 in MDMs to less than 10% of control level for at least 7 days (data not shown). As with the results obtained using 293T and HeLa cell lines, the siGemin2 duplex did not significantly affect HIV-1 expression when introduced into MDMs 24 h after infection (Fig. 4B, right panel).

Finally, we addressed the effect of depletion of Gemin2 on HIV-1 cDNA synthesis and subsequent integration using real-

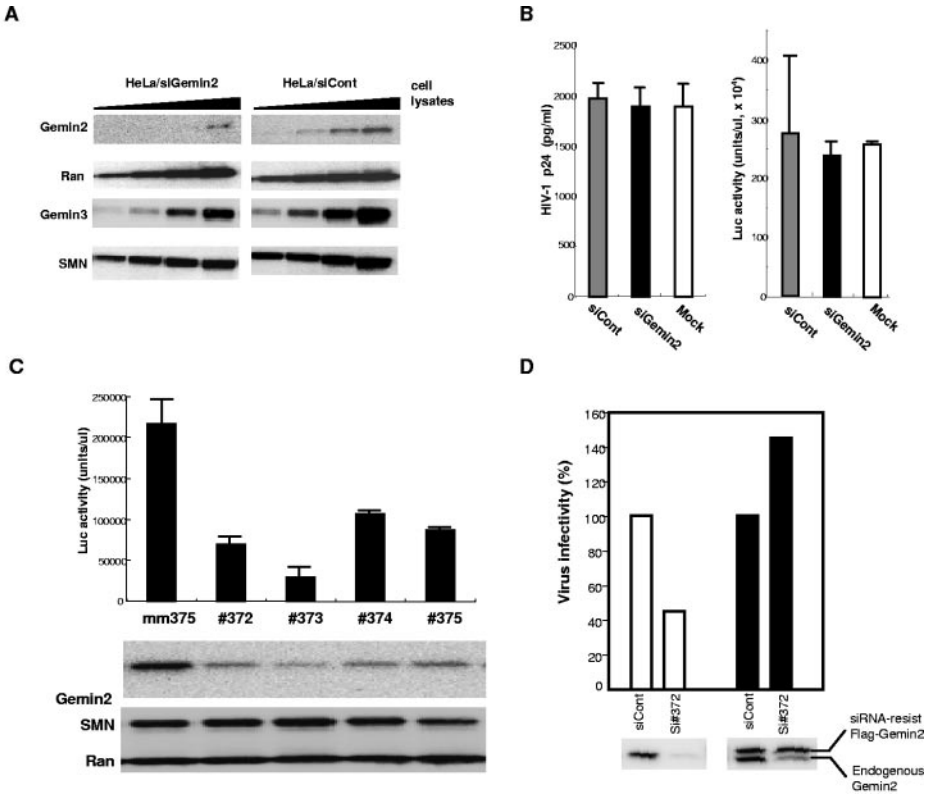

FIG. 3. Involvement of cellular Gemin2 in HIV-1 replication. (A) Total HeLa cell lysates prepared 48 h after transfection of siGemin2 (HeLa/siGemin2) or control siGFP (HeLa/siCont) were serially diluted twofold followed by Western blot analysis with antibodies against Gemin2, Ran, Gemin3, and SMN. (B) 293T cells were transfected with siGemin2 (black bar), siGFP (siCont; gray bar), or no siRNA (Mock; white bar), together with pNL-lucΔenv vector and pJD-1. The level of virus release from these 293T cells was determined by measuring HIV-1 p24 concentrations in the culture supernatant (left panel) 48 h posttransfection. These virus-containing supernatants were then incubated with HeLa cells. The cells were harvested 48 h postinfection and subjected to a luciferase assay (right panel). (C) HeLa cells were transfected with Stealth-siGemin2 (#372, #373, #374, or #375) or the control mismatch siGemin2 (mm375) 48 h before infection with HIV-1 pseudotype virus. The cells were harvested 48 h postinfection and subjected to a luciferase assay (upper panel) and Western blotting for Gemin2, SMN, and Ran (lower panel). (D) 293T cells were transfected with siRNA-resistant Flag-Gemin2 expression vector (black bars) or control empty vector (white bars) together with siGemin2#372 (si#372) or control siRNA (siCont) and then infected with HIV-1 pseudotype virus. The cells were harvested 24 h postinfection and subjected to a luciferase assay (upper) and Western blotting for endogenous Gemin2 and Flag-Gemin2 (lower). Virus infectivity is presented relative to the Luc activity in siCont-transfected cells, which was set to 100%.

time quantitative PCR analysis (20) in MDMs. Over time, the level of late reverse-transcription products (R/gag) was reduced in siGemin2-treated MDM (Fig. 4C) to ~5% of the level in the control siRNA-treated MDM at 48 h after HIV-1 infection (Fig. 4D). Of note, the amount of the early products of reverse transcription (R/U5) in the siGemin2-treated MDM was 30% to 40% of the level in the control siGFP-treated MDM (Fig. 4D). The region amplified for detection of the early reverse-transcription products (R/U5) is duplicated in the complete or nearly complete form of viral cDNA (late reverse transcription; R/gag) during the reverse-transcription step. Therefore, the marked reduction in the late reverse-transcription products by siGemin2 would be in part a consequence of the reduction in the duplication of the R/U5 region. The reduced amounts of the two-long terminal repeat (2-LTR) or integrated forms of cDNA observed in the siGemin2-treated MDMs could also be attributed to the inhibition of viral cDNA synthesis (2-LTR and integration; Fig. 4D). Thus, the dramatic reduction in the levels of late reverse-transcription products in the siGemin2-treated MDMs indicates that the abrogation of the reverse transcription of viral RNA might occur before or during the second template switch needed to complete the double-stranded viral cDNA copy, suggesting a role for Gemin2 during reverse transcription of the HIV-1 genome in vivo. We also confirmed that siGemin2 produced a similar effect on late RT products in HeLa cells. However, the inhibitory effect of siGemin2 on late RT products in HeLa cells was weaker than that in MDMs (data not shown). Therefore, possible roles of Gemin2 at other steps, including nuclear transport and integration of viral cDNA, cannot be ruled out.

Involvement of other constituents of the SMN complex. Under our experimental conditions, reduction of Gemin2 by siGemin2 was accompanied by slight decreases in SMN and Gemin3 levels (Fig. 3A and 4A). We addressed the critical point of whether Gemin2 acts on HIV-1 through the SMN complex or through another, unknown, complex by use of siRNAs targeting the other Gemin2-related proteins constituting the SMN complex. For each constituent of the complex—SMN (26), Gemin3 (6), Gemin4 (7), and Gemin6 (34)—we synthesized two or three chemically modified siRNA duplexes

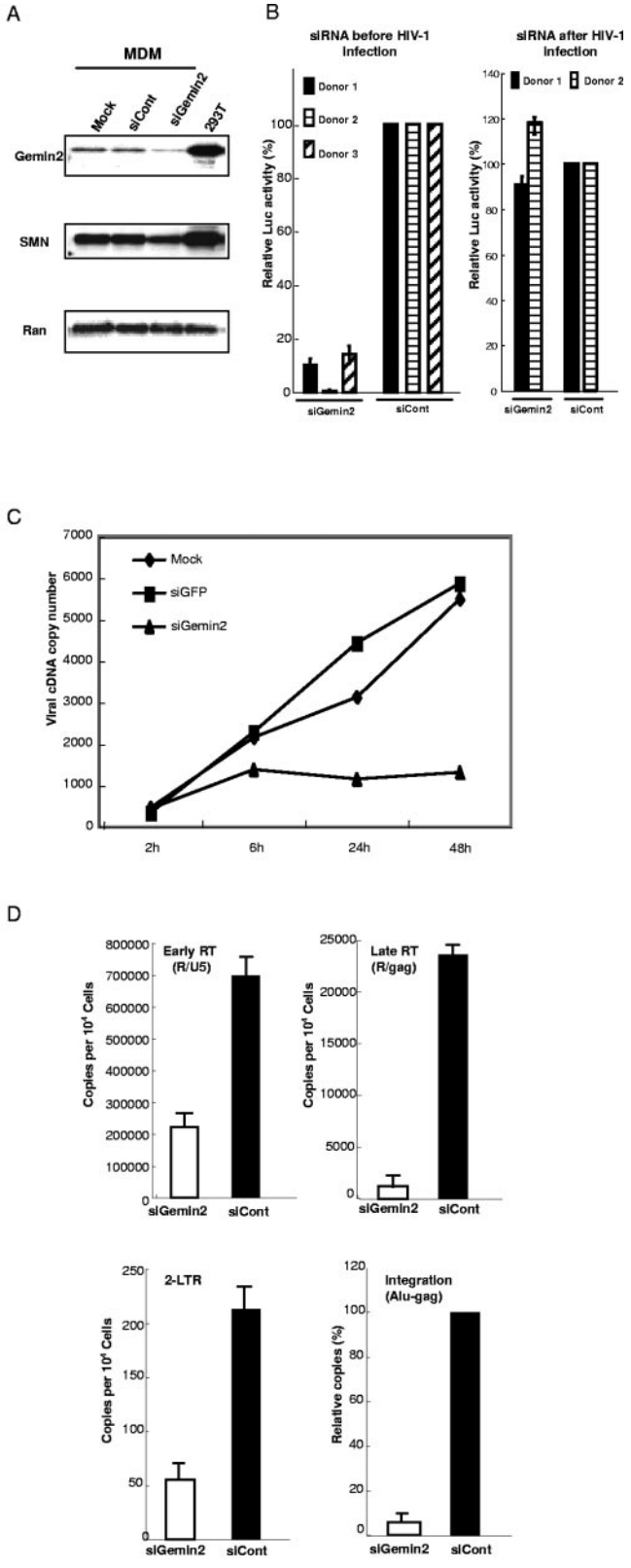

FIG. 4. Effect of siGemin2 on HIV-1 infection and cDNA synthesis in primary MDMs. (A) MDMs were transfected with siGemin2 or control siGFP (siCont) and subjected to Western blot analysis for Gemin2, SMN, and Ran. Mock, mock infected. (B) MDMs were transfected with each siRNA 24 h before (left panel) or after (right panel) infection with HIV-1 pseudotype virus. Cells were harvested and subjected to a luciferase assay 48 h (left panel) or 72 h (right panel) after infection. Relative Luc activity was calculated as a percentage of the control value in siCont-transfected cells. Each bar represents the value determined using MDMs prepared from different donors. Means ± SE from duplicate assays are shown. (C) MDMs were transfected with each siRNA 24 h before HIV-1 infection. Total DNA was extracted from siGemin2- or control siGFP-transfected MDMs at 2, 6, 24, and 48 h postinfection. Each sample was subjected to a quantitative analysis of viral cDNAs using real-time quantitative PCR with the primer pair M667-M661 (R/gag region) to measure the amount of complete or nearly complete viral cDNA (late RT). (D) Total DNA was extracted from MDMs transfected with siGemin2 or siGFP (siCont), infected with HIV-1 pseudotype virus for 48 h, and subjected to a quantitative analysis of viral cDNAs by use of real-time quantitative PCR with primer pair M667-AA55 (R/U5 region) for viral cDNA (Early-RT) or primer pair M667-M661 (R/gag region) for complete or nearly complete viral cDNA (Late-RT). We also monitored the formation of 2-LTR circular DNA by use of a primer pair that amplifies a sequence unique to the 2-LTR DNA junction and monitored the level of the integrated form of each viral cDNA by the Alu-PCR method using HIV-1-specific (M661) and Alu (Integration) primers. Results represent means ± SE.

targeting different sites within the coding sequence. Then we evaluated the effects of each siRNA on HIV-1 infection in HeLa cells (Fig. 5A). In parallel, the specific reduction in protein caused by each siRNA was also determined by examining protein expression profiles of the SMN constituents (Fig. 5B). Reduction of Gemin2 or SMN significantly blocked HIV-1 infection without showing apparent cell toxicity. However, siRNA duplexes against the SMN also significantly reduced Gemin2 levels (siSMN#271 and siSMN#272; Fig. 5B). In repeated experiments, the inhibitory effects of siSMNs on HIV-1 always correlated with the level of indirect reduction of Gemin2. Meanwhile, the reduction of Gemin3, Gemin4, and Gemin6 levels through their respective siRNA duplexes did not significantly affect HIV-1 infectivity, although siGemin3#432 and siGemin6#950 did inhibit HIV-1 infection by causing high cell toxicity. These results suggest that among the SMN constituents, Gemin2 is a critical constituent necessary to support HIV-1 infection. Thus, the effect of Gemin2 on HIV-1 infectivity might be independent of the other constituents of the SMN complex.

DISCUSSION

In this study, we have provided evidence that a novel host protein binds to HIV IN and modulates HIV-1 cDNA synthesis in vivo. We identified residues 137 to 238 of Gemin2 as binding to IN. In both the yeast two-hybrid system and a GST pull-down assay, the COOH-terminal domain of the IN was shown to be the minimum domain responsible for binding to Gemin2 (Fig. 1), although the central domain of the IN partly contributed to the binding. Gemin2 is a constituent of the SMN complex, along with other Gemin family proteins, including the putative DEAD box helicase dp103/Gemin3 (6), Gemin4 (7), Gemin5 (18), Gemin6 (34), and Gemin7 (2). Under our experimental conditions, treatment of cells with siGemin2 reduced the amount of Gemin2 protein and also resulted in slight decreases of SMN and Gemin3 levels (Fig. 3A and 4A).

Although the exact role of Gemin2 in the snRNP complex

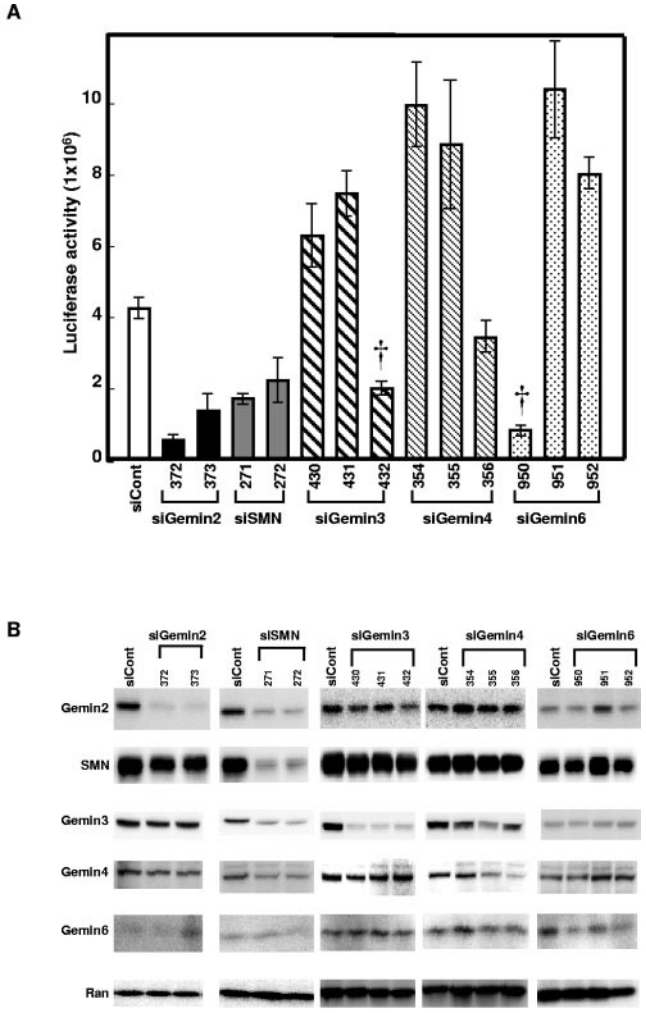

FIG. 5. Involvement of other constituents of the SMN complex. (A) HeLa cells were transfected with the Stealth siRNAs targeting Gemin2, Gemin3, Gemin4, Gemin6, or SMN 48 h before infection with HIV-1 pseudotype virus. The mismatch siGemin2 (mm375) was used as a negative control siRNA (siCont). The cells were harvested 48 h postinfection and subjected to a luciferase assay. Each bar represents the means ± SE. †, less than 20% of cells were viable 48 h after siRNA transfection. (B) Aliquots of the same cells harvested for the luciferase assay as described for panel A were subjected to Western blot analysis for Gemin2, SMN, Gemin3, Gemin4, Gemin6, and Ran.

remains to be determined, some reports suggest that it has a critical role in the assembly of the snRNP complex in the cytoplasm (3, 21, 30). More recently, the roles of the individual SMN constituents were addressed by using RNA interference (14). Feng et al. showed that a reduction of SMN leads to a decrease in snRNP assembly, the disappearance of bodies called Gems where SMN and Gemin2 are concentrated in the nucleus, and a drastic reduction in the amounts of several Gemins. Moreover, reduction of Gemin2 or Gemin6 levels strongly decreases the activity of the SMN complex. Therefore, we cannot exclude the possibility that a reduction of Gemin2 might also reduce SMN function under our experimental conditions. However, our data obtained using siRNAs targeting SMN, Gemin3, Gemin4, or Gemin6 suggest that Gemin2 is a critical constituent of the SMN complex for support of HIV-1 infection (Fig. 5). It seems likely that Gemin2 acts on the HIV-1 preintegration complex, either alone or with as-yet-unknown proteins other than the SMN constituents, although this point remains to be confirmed. In addition to the full-length Gemin2 (termed Gemin2-alpha), three splicing variants of Gemin2 (Gemin2-beta, -gamma, and -delta) have been identified (1). Gemin2-alpha has found to be ubiquitously expressed at high levels in the various normal tissues. In contrast, Gemin2-beta and -gamma are expressed at very low levels in these normal tissues (1). The Gemin2 residues that we identified as the region of Gemin2 that binds IN in the yeast two-hybrid system (residues 137 to 238, IBDG2) were shared by all splicing variants of Gemin2 except Gemin2-beta, in which residues 174 to 188 are deleted. It will be interesting to identify the contribution of other splicing variants of Gemin2 to HIV-1 infection.

The SMN complex has recently been reported to be generally used by infectious agents for RNP assembly (17). Golembe et al. demonstrated that herpesvirus saimiri uses the SMN complex to assemble Sm cores on its small RNAs (HSURs), just as occurs with host snRNPs. HSURs are the most abundant viral transcripts in latently infected, transformed T cells but are not essential for viral replication. Thus, the biological meaning of their complex formation remains to be determined. However, the authors suggest that infectious agents that engage the SMN complex may burden SMN-dependent pathways, possibly leading to a deleterious reduction in the availability of SMN complexes for essential host functions.

In the case of HIV-1 infection, we showed here that HIV-1 might require Gemin2 for efficient viral cDNA synthesis. Our results suggest that Gemin2, either alone or in concert with unidentified cellular proteins, supports HIV-1 infection, probably by supporting the reassembly of the reverse transcription complex to initiate and complete reverse transcription. Several cases of mutations in HIV-1 IN affecting reverse transcription have been described previously (11, 29, 37, 39, 42). It is, therefore, reasonable that a protein interacting with IN might play a role in reverse transcription and could also be involved in the subsequent nuclear transport and integration of viral cDNA. Since both reverse transcription and integration are essential steps for retrovirus infection, our findings will shed light on the functional role of IN during the reverse transcription of the retroviral genome and will also serve as the basis for a novel therapeutic approach to treat HIV-1 disease.

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